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CALCULATING GEOMETRIC PARAMETERS FOR INDUSTRIAL ROBOT GRIPPER MECHANISM ACCORDING TO THE ASSUMED FUNCTIONAL CHARACTERISTICS

WYZNACZANIE PARAMETRÓW GEOMETRYCZNYCH MECHANIZMU CHWYTAKA ROBOTA PRZEMYSŁOWEGO DLA ZAŁOŻONYCH CHARAKTERYSTYK FUNKCJONALNYCH

A b s t r a c t

The paper presents an approach to optimal synthesis of robot gripper mechanism. There are two different patterns of force and displacement functional characteristics applied. The first one deals with the assumed linear or nonlinear displacement of the gripper ends, whereas the second one takes under consideration the constant value or nonlinear chart of the gripping force. In order to generate the optimal solutions a gradient based method, a random search method and an evolutionary algorithm are used. The obtained results show relatively good effectiveness of the proposed optimization approach in comparison to conventional methods of synthesis of linkage mechanisms. The best solutions were generated by the evolutionary algorithm based method; worse by the random search algorithm. Gradient based method fails during optimization process and should not be used for such type of problems, especially described by trigonometric functions.

Keywords: industrial robots, linkage mechanism synthesis, design optimization, evolutionary algorithms

S t r e s z c z e n i e

W artykule przedstawiono metodę wyznaczania parametrów geometrycznych mechanizmu chwytaka dźwigniowego robota przemysłowego. Zastosowano syntezę mechanizmu dla założonych charakterystyk funkcjonalnych mechanizmu. Założono przebiegi liniowe i nieliniowe charakterystyki siłowej i przemieszczeniowej. W obliczeniach wykorzystano trzy algorytmy, gradientowy, losowy i ewolucyjny. Otrzymane wyniki wskazują, że proponowane podejście optymalizacyjne jest możliwe do zastosowania i stosunkowo efektywne w porównaniu z tradycyjnymi metodami syntezy mechanizmów, przy czym możliwe okazało się zastosowanie wyłącznie algorytmu ewolucyjnego generującego najlepsze rozwiązania w każdym przypadku oraz znacznie gorszego algorytmu losowego. Nie udało się w ogóle wygenerować rozwiązań algorytmem gradientowym, co wskazuje, że dla zadań optymalizacyjnych opisywanych funkcjami trygonometrycznymi tego typu algorytmy są zawodne i nie powinny być stosowane.

Słowa kluczowe: roboty przemysłowe, synteza mechanizmu dźwigniowego, optymalizacja konstrukcji, algorytmy ewolucyjne

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1. Introduction

The design of many linkage mechanisms consist of two main steps. The first one is choosing a structure of the mechanism and the second one is calculating geometric parameters [3, 12–14]. These parameters are mainly linear or angular dimensions of mechanism, work ranges of movable parts, etc. The generation of geometric dimensions is implemented in order to obtain assumed motion parameters according to their functions and purposes, including kinematical and dynamical analysis. For kinematic analysis, there are graphical, analytical and numerical approaches used so far [15]. In fact, currently, these methods come down to numerical calculations of nonlinear equation systems. Numerical methods can be based on an iterative process of solving nonlinear equations, for example by Newton–Raphson algorithm [2]. This algorithm uses analytical or graphical dependences for position calculations of mechanism parts or their joints, and then uses the method of finite increments to generate their velocity and acceleration. The numerical approach may also include a method based on the use of an expansion of the function into the trigonometric Fourier series. Other approaches, quite often used for geometric synthesis, are optimization based methods. The problem of optimum design of different mechanisms has a quite long history. Most of these problems are modeled by means of nonlinear programming [1, 2, 5–7]. In many cases, calculation of these models by means of conventional optimization methods might give worse solutions or be difficult, or even impossible. Thus, in the last two decades, evolutionary algorithms (EAs) have become an effective tool to solve difficult optimization tasks, including continuous, discrete and mixed ones. Searching for optimal geometric parameters of gripper linkage mechanisms is an example of such a complicated task. Moreover, the optimization problem can have a multicriteria character in which several criteria are to be considered, so the EAs can also be used to obtain the full set of Pareto optimal solutions (non-dominated solutions) while single run of the EA. According to the advantages of EAs mentioned above, there is the possibility of using EAs firstly for parametrical optimization of different mechanism structures and then for finding the best structure of robot gripper mechanism. The problem of finding the best structure of mechanism is not considered in the paper. During the parametrical optimization, different traditional and heuristic algorithms are compared in order to find the best method for the described problem. In general, the optimization problem of robot gripper mechanism can be formulated as follows:
find:

$$\mathbf{x}^* = [x_1^*, x_2^*, ..., x_I^*] \tag{1}$$

which will satisfy the K inequality constraints and J equality constraints

$$g_k(\mathbf{x}^*) \geq 0, \text{ for } k = 1, 2, \ldots, K \tag{2}$$

$$h_j(\mathbf{x}^*) = 0, \text{ for } j = 1, 2, \ldots, J \tag{3}$$

and optimize the vector function:

$$\mathbf{f}(\mathbf{x}^*) = \min\,[f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_N(\mathbf{x})] \tag{4}$$

where: $\mathbf{x} = [x_1, x_2, ..., x_I]$ is the vector of decision variables, $\mathbf{f}(\mathbf{x}) = [f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_N(\mathbf{x})]$ is the vector of objective functions. Elements of vector $\mathbf{x}$ represent the dimensions of robot gripper elements, whereas the elements of vector $\mathbf{f}(\mathbf{x})$ represent the optimization criteria.

2. Problem formulation

The optimization problem is formulated as searching geometrical dimensions of the mechanism for the single criteria minimization of pattern deviation for the given force and displacement functional characteristics. The linkage mechanism is considered as an ideal one, with stiff elements and without friction forces in the joints.

2.1. Force and displacement dependences

Let us consider a gripper mechanism with the given kinematical structure as in Fig. 1. Force dependences are worked out for a static equilibrium for the whole range of mechanism movement.

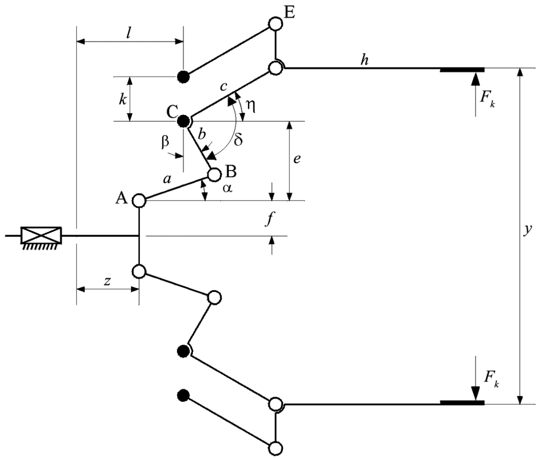

Fig. 1. Scheme of a robot gripper mechanism

The geometrical dependencies of the gripper mechanism are presented in Fig. 2 and evaluated as follows:

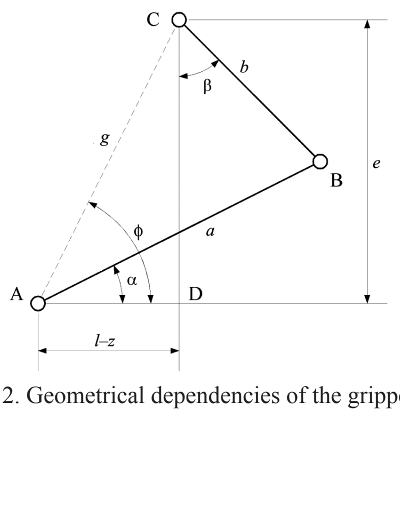

Fig. 2. Geometrical dependencies of the gripper mechanism

$$g = \sqrt{(l-z)^2 + e^2} \tag{5}$$

$$b^2 = a^2 + g^2 - 2 \cdot a \cdot g \cdot \cos(\phi - \alpha) \tag{6}$$

$$\alpha = \phi - \arccos\left(\frac{a^2 + g^2 - b^2}{2 \cdot a \cdot g}\right) \tag{7}$$

$$a^2 = b^2 + g^2 - 2 \cdot b \cdot g \cdot \cos\left(\beta + \frac{\pi}{2} - \phi\right) \tag{8}$$

$$\beta = \arccos\left(\frac{b^2 + g^2 - a^2}{2 \cdot b \cdot g}\right) + \phi - \frac{\pi}{2} \tag{9}$$

$$\phi = \arctan\left(\frac{e}{l-z}\right) \tag{10}$$

$$\eta = \beta + \delta - \frac{\pi}{2} \tag{11}$$

$$y(\mathbf{x}, z) = 2 \cdot (e + f + c \cdot \sin(\eta)) \tag{12}$$

The gripping force is calculated as follows:

$$F_k(P, \mathbf{x}, z) = \frac{P \cdot b \cdot \sin(\alpha + \beta) \cdot \cos(\eta)}{2 \cdot c \cdot \cos(\alpha)} \tag{13}$$

2.2. Optimization model of the gripper mechanism

For the given dependences the optimization model is presented below. The vector of decision variables is: $\mathbf{x} = [a, b, c, e, f, l, \delta]^T$, where a, b, c, e, f, l, are dimensions of the gripper and δ is the angle between the elements b and c.

The objective functions can be evaluated in general form as follows:

$$f_1(\mathbf{x}, z) = \int_z \left[y^{\text{assumed}}(z) - y(\mathbf{x}, z) \right]^2 \cdot dz \tag{14}$$

$$f_2(P, \mathbf{x}, y) = \int_y \left[F_k^{\text{assumed}}(y) - F_k(P, \mathbf{x}, y) \right]^2 \cdot dy \tag{15}$$

where:

- the functions $y^{\text{assumed}}(z)$ and $F_k^{\text{assumed}}(y)$ are respectively assumed displacement and force patterns of functional characteristics,
- $Z_{\min} \le z \le Z_{\max}$, $Y_{\min} \le y \le Y_{\max}$ are respectively lower and upper bounds of displacements z and y.

All the objective functions are to be minimized.

Note that objective functions depend on the vector of decision variables and on the displacement z. Thus, for the given vector x, the values of the functions have to be evaluated for different values of z, which makes the objective functions computationally expensive and the problem becomes more complicated than a general nonlinear programming problem. From the geometry of the gripper and based on the mechanism movement, the following constraints can be derived:

$$g_1(\mathbf{x}) = y(\mathbf{x}, z) \ge 0 \text{ for each } z \text{, were } Z_{\min} \le z \le Z_{\max}, \tag{16}$$

$$g_2(\mathbf{x}) = \alpha + \frac{\pi}{2} \geq 0 \text{ for each } z\text{, were } Z_{\min} \leq z \leq Z_{\max} \tag{17}$$

$$g_3(\mathbf{x}) = \frac{\pi}{2} - \alpha \geq 0 \text{ for each } z\text{, were } Z_{\min} \leq z \leq Z_{\max} \tag{18}$$

$$g_4(\mathbf{x}) = \eta + \frac{\pi}{2} \geq 0 \text{ for each } z\text{, were } Z_{\min} \leq z \leq Z_{\max} \tag{19}$$

$$g_5(\mathbf{x}) = \frac{\pi}{2} - \eta \geq 0 \text{ for each } z\text{, were } Z_{\min} \leq z \leq Z_{\max} \tag{20}$$

$$h_1(\mathbf{x}) = z + a \cdot \cos(\alpha) - b \cdot \sin(\beta) - l = 0 \text{ for each } z\text{, were } Z_{\min} \leq z \leq Z_{\max} \tag{21}$$

$$h_2(\mathbf{x}) = a \cdot \sin(\alpha) + b \cdot \cos(\beta) - e = 0 \text{ for each } z\text{, were } Z_{\min} \leq z \leq Z_{\max} \tag{22}$$

3. Applied Methods of Solution

The problem was considered as continuous nonlinear programming problem. In order to generate optimal solutions, the following three different algorithms were applied:

– conjugate gradient algorithm (CGA) [6, 10],
– random search method (RSM) [6],
– evolutionary algorithm (EA) [7, 9].

The gradient based method is used with the very well known rules:

$$x^{t+1} = x^t + \alpha^t \nabla\phi(x^t) \tag{23}$$

where: α^t is the step length, $\nabla\phi(x^t)$ is the gradient of $\phi(x^t)$ at the point x^t and is given using the formula:

$$\phi(\mathbf{x}, r) = f(\mathbf{x}) + r\sum_{m=1}^{M}\left[h_m(\mathbf{x})\right]^2 + r\sum_{k=1}^{K} G_k\left[g_k(\mathbf{x})\right]^2 \tag{24}$$

where: G_k is the Heaviside operator such that $G_k = 0$ for $g_k(\mathbf{x}) \geq 0$ and $G_k = 1$ for $g_k(\mathbf{x}) < 0$, r is a positive multiplier, which controls the magnitude of the penalty terms.

The calculations for each run were carried out using several different starting points x^0, the step α^t and number of iterations were assumed automatically in order to achieve assumed accuracy equal to 0.000001, multiplier r =10 000.

As the random search method, the most common exploratory algorithm called Monte Carlo is used. In the method, a certain number of points is picked at random over the estimated range of all variables. This may be done formally by obtaining the randomly selected value x_i from the following formula:

$$x_i = x_i^l + \rho_i\left(x_i^u - x_i^l\right) \tag{25}$$

where:

x_i^l – the estimated lower bound of x_i,
x_i^u – the estimated upper bound of x_i,
ρ_i – a random number between zero and one.

For the above formula, there were 40 000 points generated and compared.

As the evolutionary algorithm, the tournament selection based one is used [7, 9]. It does not require calculation of the criterion and constraints functions in any situation, so calculations can significantly speed up. The principle of operation is as follows:
– If both solutions are outside of the feasible region, the one which is closer to this region is selected for the next generation. The values of the objective function are not calculated for either of the solutions.
– If one of the solutions is in the feasible region and another one is out of this region, the one which is in the feasible region is selected for the next generation. The values of the objective function are not calculated for either of the solutions.
– If both solutions are in the feasible region, the one with the better value of the fitness function is selected for the next generation.

Parameters for the evolutionary algorithm: crossover rate $R_C = 0.6$, mutation rate $R_M = 0.01$, population size $J = 100$, number of generations $T = 400$.

4. Results of optimization process

The optimization process was run using the following data:
– Side constraints:
$0 \leq a \leq 100$, $0 \leq b \leq 100$, $10 \leq c \leq 100$, $0 \leq e \leq 100$, $0 \leq f \leq 100$, $0 \leq l \leq 100$, $0 \leq \delta \leq 3.14$.
– Additional parameters:
actuator movement ranges $Z_{min} = 0$ mm, $Z_{max} = 50$ mm, actuator force $P = 100$ N.

The aim of the optimization was to find linear and angular dimensions of the linkage mechanism for the assumed force and displacement functional characteristics. The obtained results are presented in Table 1 to 4. The comparison between the assumed patterns of functional characteristics and charts given from generated optimal solutions are shown in Fig. 3 to 10. The comparison shows that there is a possibility to improve the parameters of the gripper mechanism using a suitable optimization procedure. Note that sequential methods failed during calculation, so they cannot be used for finding optimal gripper mechanisms. Random search method and evolutionary algorithm were used for the same number of function calls. For both methods, calculations took a few minutes.

Table 1

Generated optimal solutions for the assumed linear pattern of the ends displacement

Method	$f_1(\mathbf{x}, z)$	a [mm]	b [mm]	c [mm]	e [mm]	f [mm]	l [mm]	δ [rad]	Constraints
EA	53.68	36.49	46.82	65.01	65.16	0.02	51.91	0.80	satisfied
RSM	733.57	76.27	69.45	56.38	45.31	8.01	53.30	0.25	satisfied
CGA	–	–	–	–	–	–	–	–	failed

Table 2

Generated optimal solutions for the assumed nonlinear pattern of the ends displacement

Method	$f_1(x, z)$	a [mm]	b [mm]	c [mm]	e [mm]	f [mm]	l [mm]	δ [rad]	Constraints
EA	1712.43	36.94	59.93	72.07	82.34	0.02	51.02	0.76	satisfied
RSM	4053.38	42.72	50.46	70.45	64.45	22.82	64.40	0.57	satisfied
CGA	–	–	–	–	–	–	–	–	failed

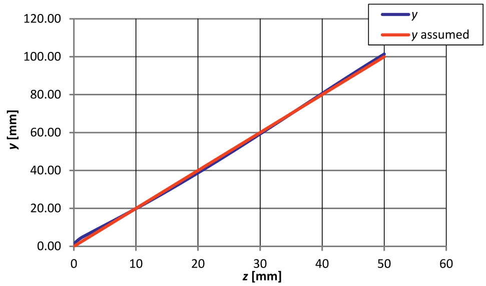

Fig. 3. Comparison of the displacement characteristics for the assumed linear pattern of the ends displacement (generated by EA)

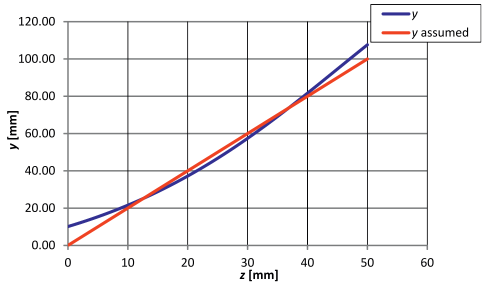

Fig. 4. Comparison of the displacement characteristics for the assumed linear pattern of the ends displacement (generated by RSM)

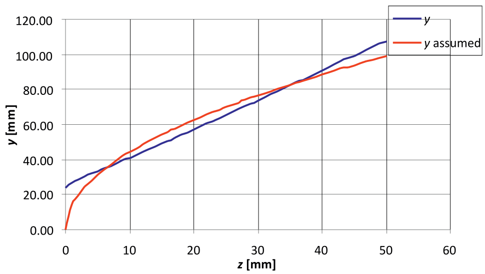

Fig. 5. Comparison of the displacement characteristics for the assumed nonlinear pattern of the ends displacement (generated by EA)

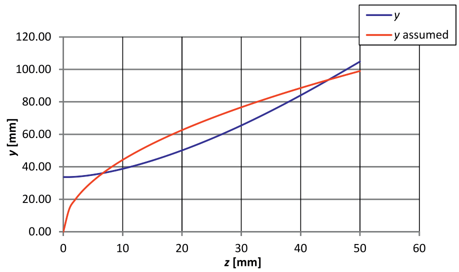

Fig. 6. Comparison of the displacement characteristics for the assumed nonlinear pattern of the ends displacement (generated by RSM)

Table 3

Generated optimal solutions for the assumed constant value of the gripping force

Method	$f_2(x, z)$	**a** [mm]	**b** [mm]	**c** [mm]	**e** [mm]	**f** [mm]	**l** [mm]	δ [rad]	**Constraints**
EA	711.61	89.00	45.00	29.20	100.00	62.90	50.00	1.30	satisfied
RSM	7092.21	84.40	67.60	34.10	82.4	25.40	50.60	1.10	satisfied
CGA	–	–	–	–	–	–	–	–	failed

Table 4

Generated optimal solutions for the assumed nonlinear pattern of the gripping force

Method	$f_2(x, z)$	**a** [mm]	**b** [mm]	**c** [mm]	**e** [mm]	**f** [mm]	**l** [mm]	δ [rad]	**Constraints**
EA	1928.61	89.60	100.00	10.00	65.80	57.10	50.70	0.50	satisfied
RSM	270690.01	53.90	52.70	10.60	74.50	48.50	50.50	0.80	satisfied
CGA	–	–	–	–	–	–	–	–	failed

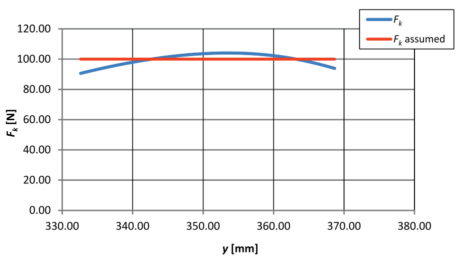

Fig. 7. Comparison of the force characteristics for the assumed constant value of the gripping force (generated by EA)

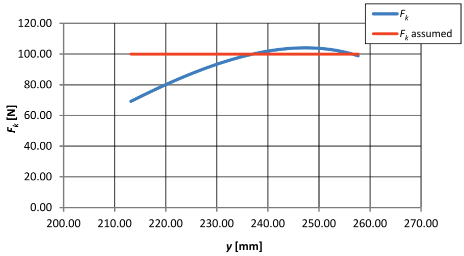

Fig. 8. Comparison of the force characteristics for the assumed constant value of the gripping force (generated by RSM)

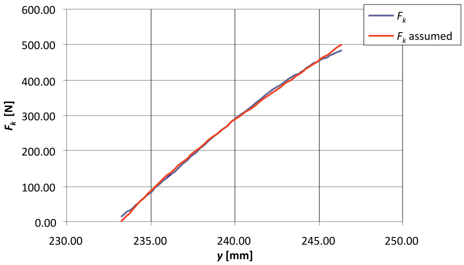

Fig. 9. Comparison of the force characteristics for the assumed nonlinear pattern of the gripping force (generated by EA)

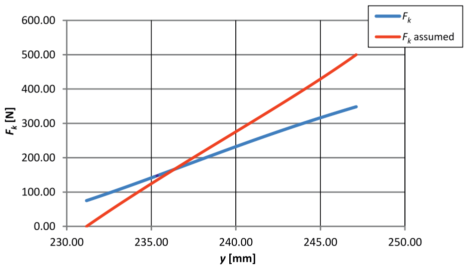

Fig. 10. Comparison of the force characteristics for the assumed nonlinear pattern of the gripping force (generated by RSM)

5. Summary

The experiments presented above indicate that the proposed optimization procedure can significantly improve functional parameters during the synthesis of the griper mechanism, especially the force and displacement characteristics. This approach has a universal character and can be used for different mechanisms. The obtained results show that conventional methods fail or give worse solutions. The conjugate gradient algorithm (CGA) was not able to generate any solution during all runs of the optimization procedure for several different starting points. The reason was a discontinuous type of the optimization model for fairly wide ranges of geometrical parameters. So, it yields that for parametrical optimization of linkage mechanisms, the use of gradient based methods is very riskful or impossible. The random search method gave feasible solutions, but they were far from the best. It seems the most suitable method to solve such problems is an evolutionary algorithm. In addition, evolutionary algorithms allow considering a multicriteria parametrical optimization. Note that, for the given kinematical structure of the linkage mechanism, the applied optimization algorithms were not able to find the solution, which has got the ideal mapped patterns of functional characteristics. It means that for generating solutions with the functional characteristics similar to the patterns, different kinematical structures of the mechanism have to be considered.

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